Dark Forces, Dark Matter, and the GeV-Scale Discovery Frontier

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New Light Weakly Coupled Particle Session
CSS Conference
July, 2013

Nice Source Summarizing Broad Physics Program:

– Intensity Frontier Meeting at Argonne (April 2013) (see posted talks)

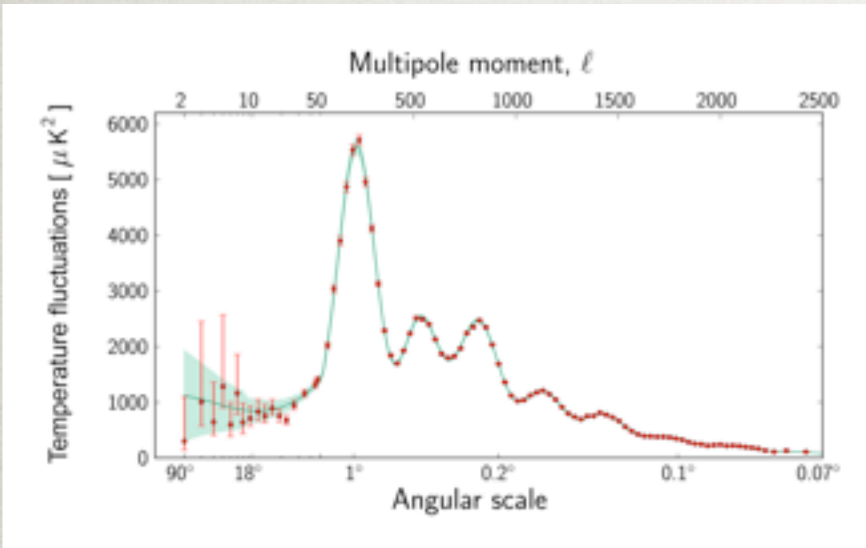
Considerable documentation to help with discussions over the next three days

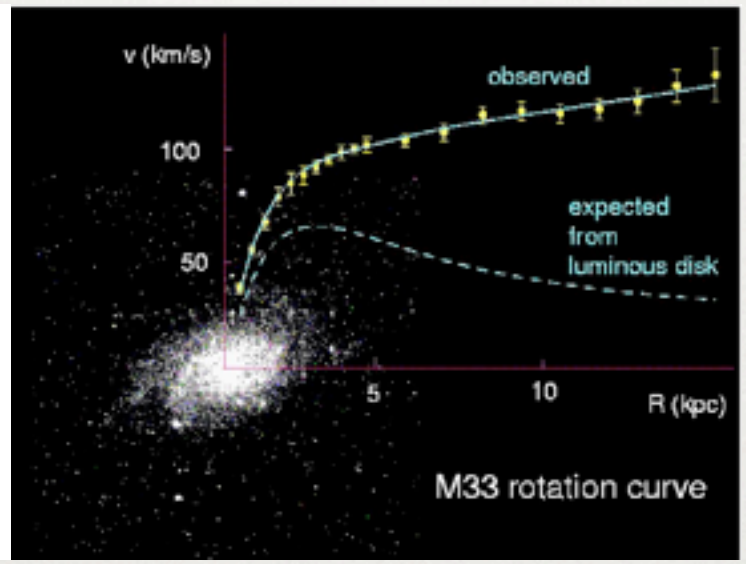
Outline

- Theory of Dark Forces & Motivation
  - Fundamental Physics Motivation
  - Dark Matter Motivation
  - Precision Anomalies
  - Dark Matter Anomalies
- What has been achieved recently
- What will be achieved in next few years
- Goals for next 10 years

Beyond the Standard Model

We know there is dark matter

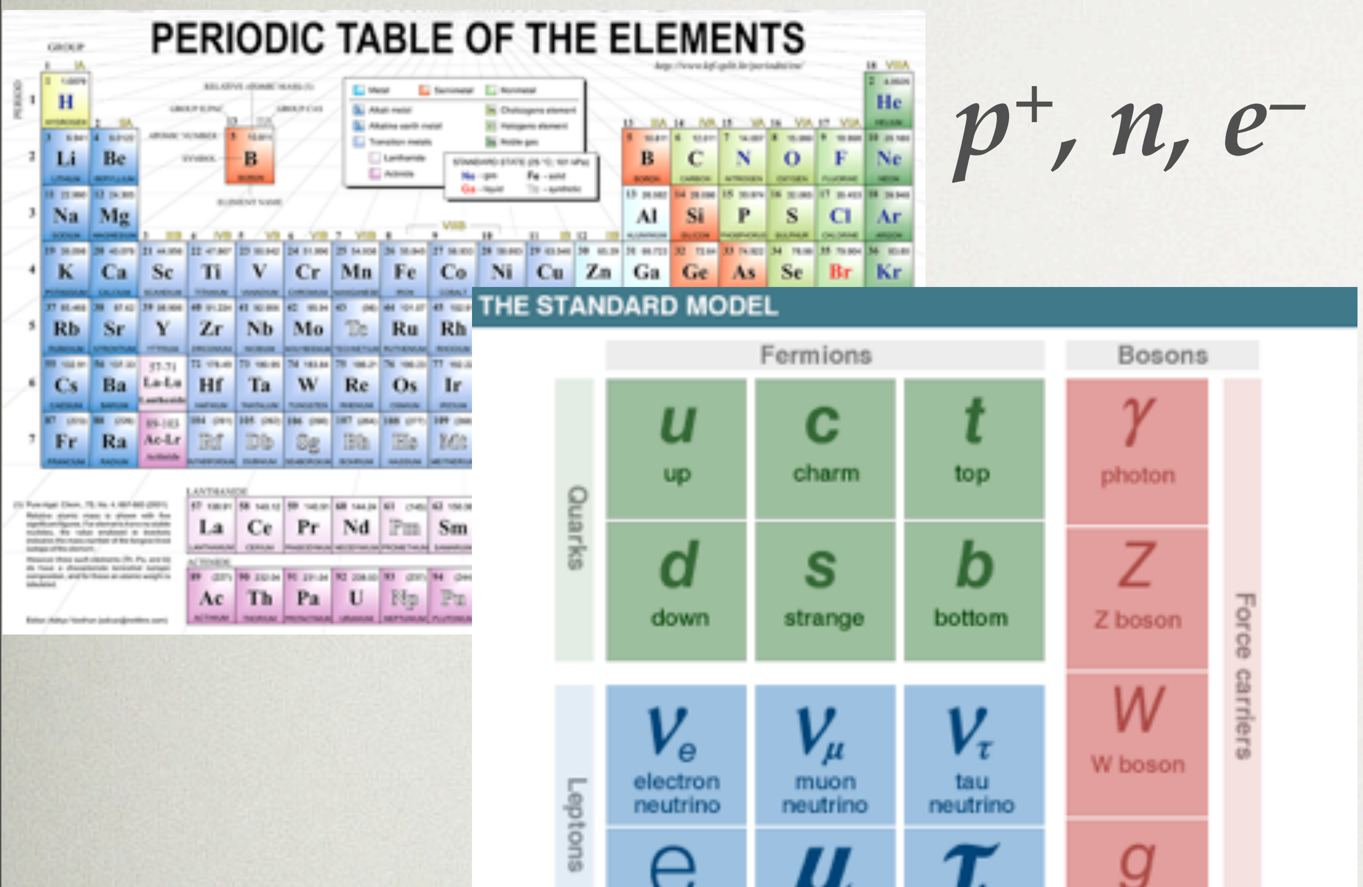




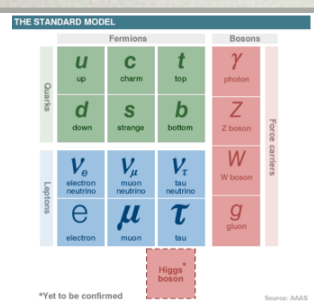
...but what is it?

LHC and direct detection results challenge connection of dark matter to "weak-scale naturalness"

Copernican Particle Physics?



p^+, n, e^-

	?	...
?	?	?

extension of Standard Model?
(axion, superpartner, ...)

Completely new physics?

What do we actually know about the dark sector?

Beyond the Standard Model

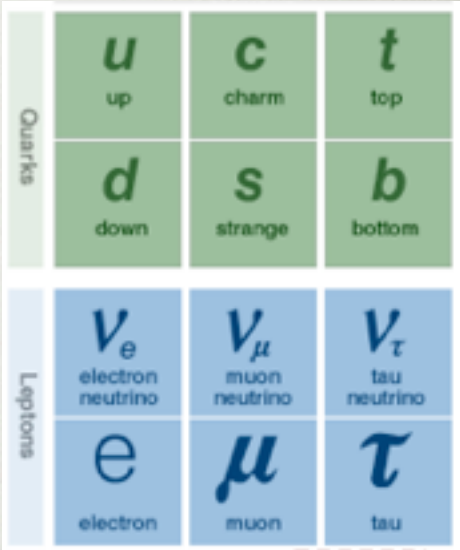
Dark Sector ?

$$U(1)_D \times \ldots$$

$$U(1)_Y \times SU(2)_W \times SU(3)_s$$

Look for interactions allowed symmetry!

Beyond the Standard Model



Known matter interacts through three gauge forces (strong, weak, and electromagnetic)

LHC looking for new matter *interacting through the same forces*

...but what about **matter that is not charged under these forces?**

Gauge- & Lorentz-invariance *restrict possible interactions* with such matter to high dimension operators. New sub-GeV matter can be consistent.

The "Portals"

Searches can be organized around a small number of interactions allowed by Standard Model symmetries

Higgs Portal	$\epsilon_h \, \lvert h\rvert^2 \lvert\phi\rvert^2$	exotic rare Higgs decays?
Neutrino Portal	$\epsilon_\nu \, (hL)\psi$	not-so-sterile neutrinos?
Vector Portal	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$	kinetic mixing?
Axion Portal	$\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$	axion-like particles?

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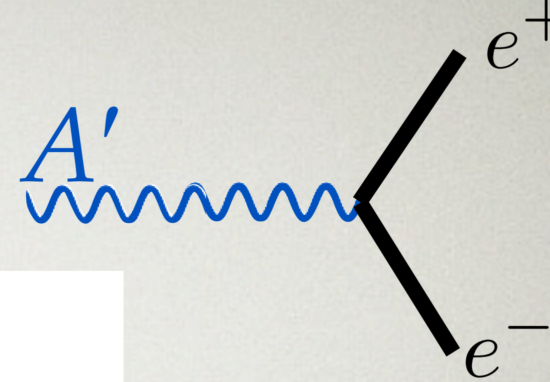
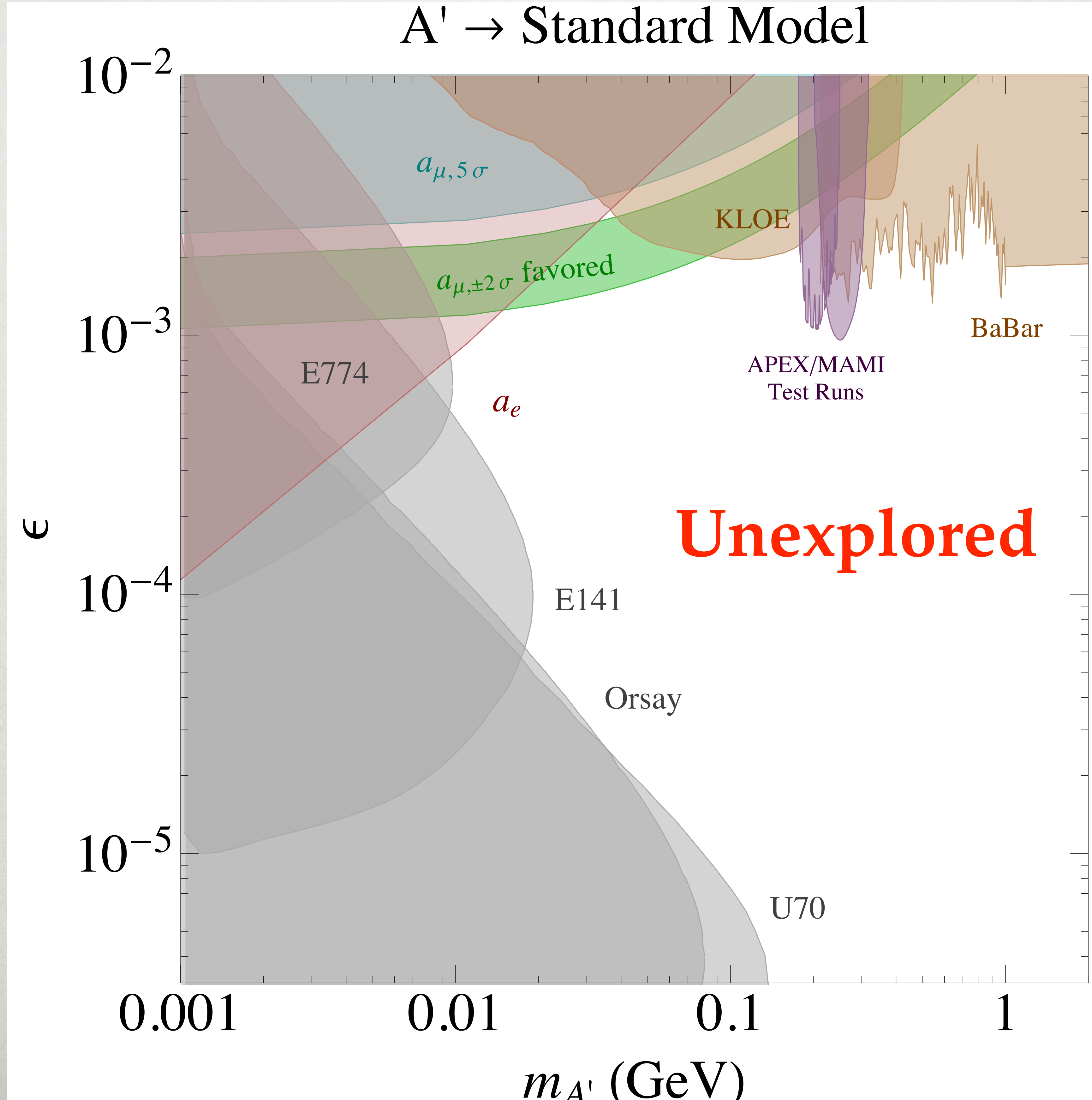
Vector Portal	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$	Focus of this talk
Axion Portal	$\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$	axion-like particles?

The Territory

(A′ Electron/Muon Decays)

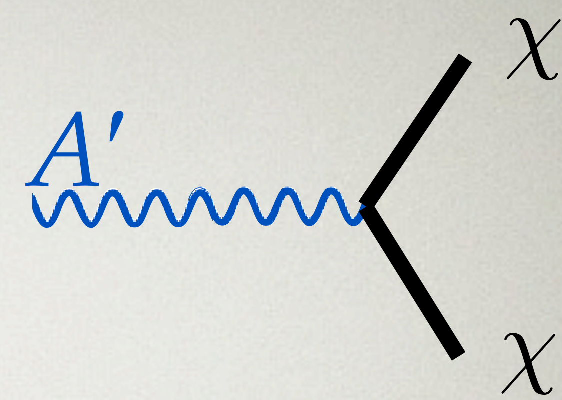


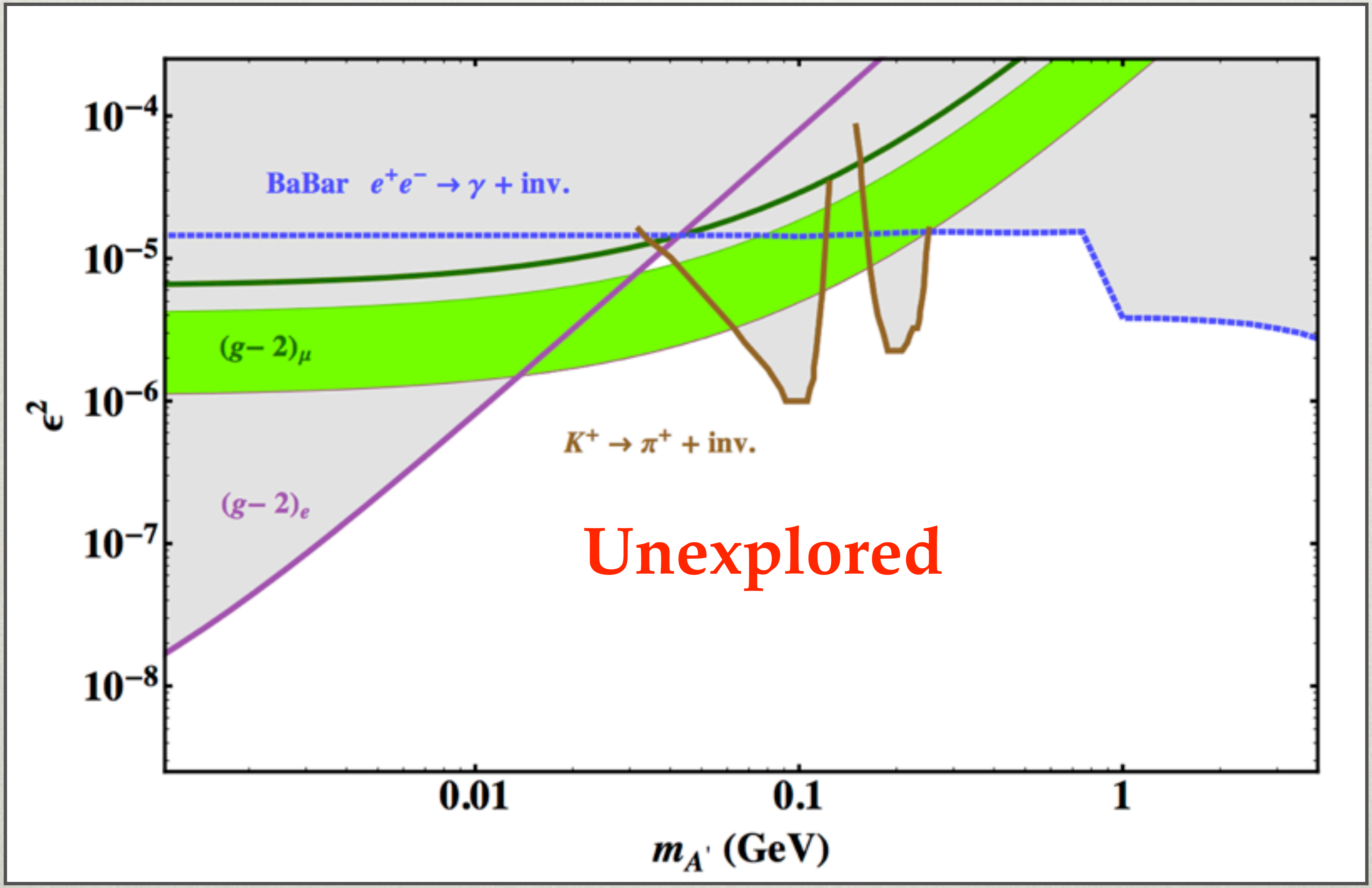


9

The Territory

(A′ invisible "dark matter" Decays)



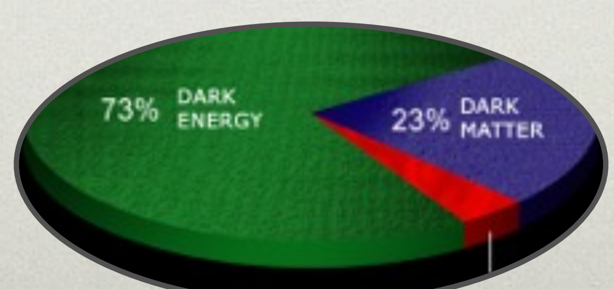


(Izaguirre, Krnjaic, PS, Toro)

GeV-Scale Discovery Frontier

Tremendous opportunity to explore GeV-Scale dark matter and weakly coupled physics with novel small-scale experiments!

What will we find?



11

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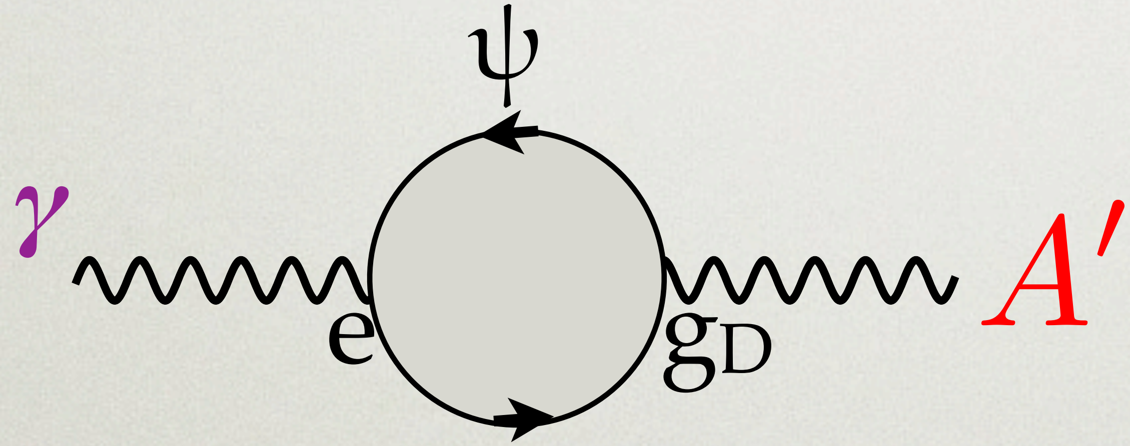
Sources and Sizes of Kinetic Mixing $\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$

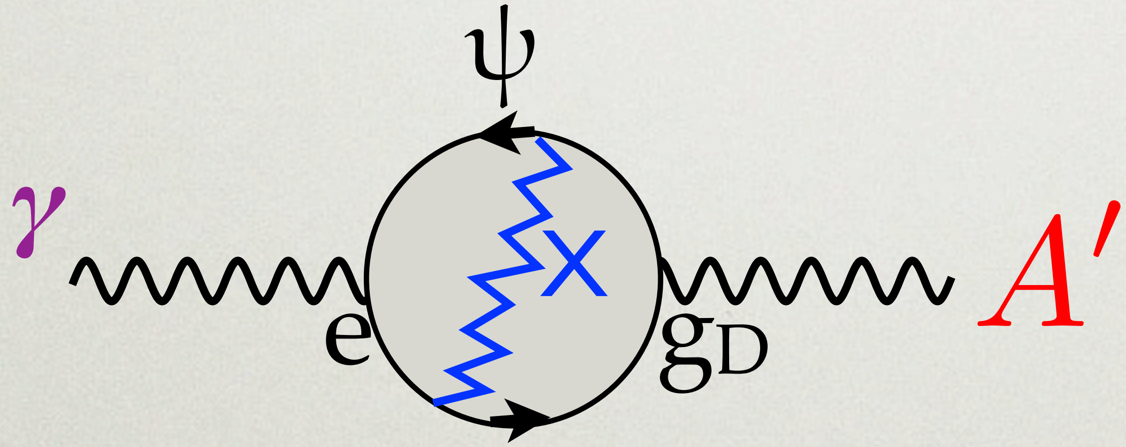
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



generates $\epsilon \sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}$

Sources and Sizes of Kinetic Mixing $\frac{1}{2}\epsilon_Y\, F^Y_{\mu\nu} F'^{\mu\nu}$

- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - In Grand Unified Theory, symmetry forbids tree-level & 1-loop mechanisms. GUT-breaking enters at 2 loops



generating $\epsilon \sim 10^{-3} - 10^{-5}$

($\rightarrow 10^{-7}$ if both U(1)'s are in unified groups)

Sources and Sizes of Mass Term

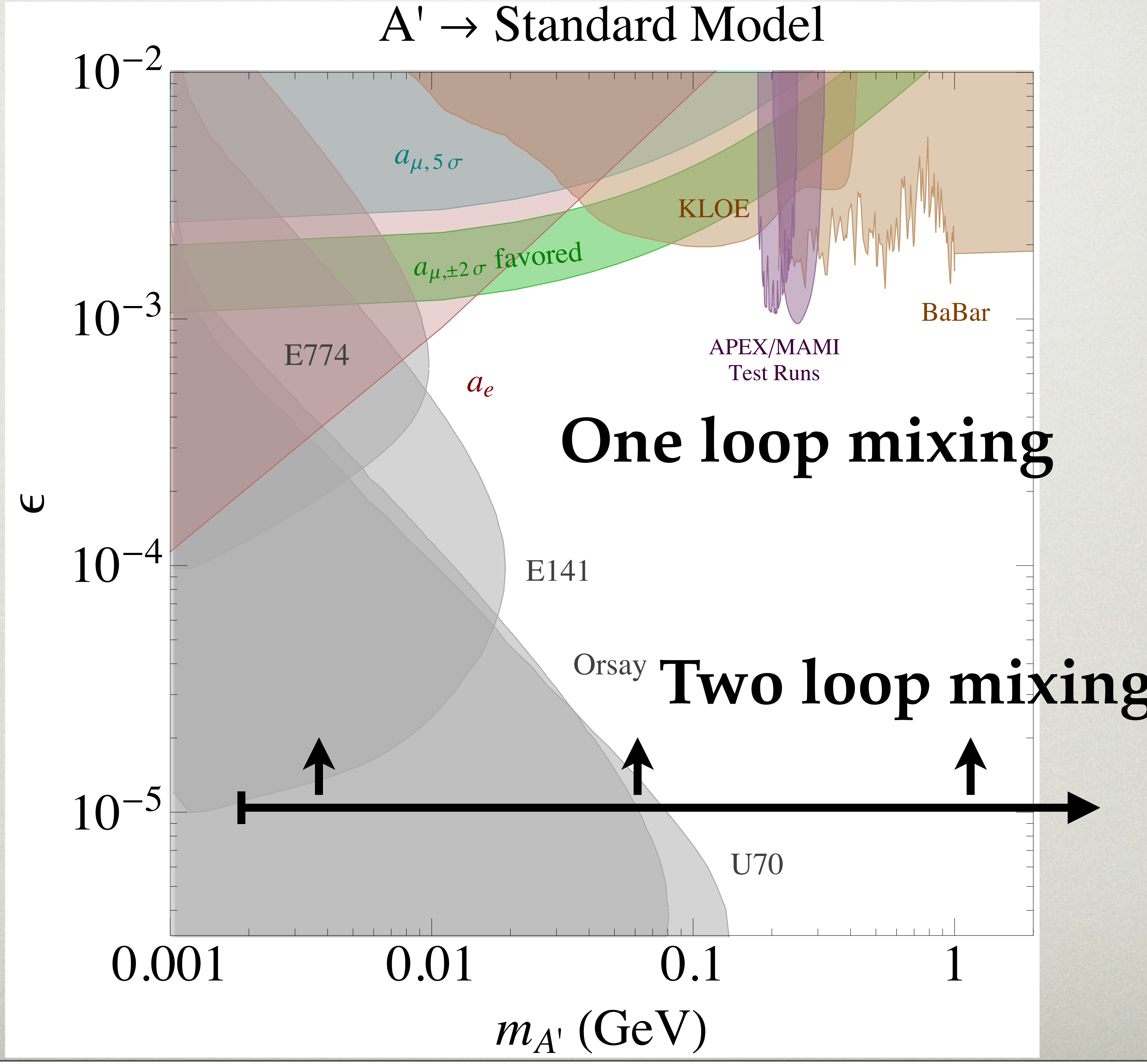
- sub-MeV: non-perturbative physics (like Λ_{QCD})
- MeV-to-GeV is motivated by g-2 and dark matter anomalies
- Possible origin: related to M_Z by small parameter
  - e.g. supersymmetry+kinetic mixing $\Rightarrow$ scalar coupling to SM Higgs, giving

$$m_{A'} \sim \sqrt{\epsilon}\, M_Z \lesssim 1\mathrm{GeV}$$

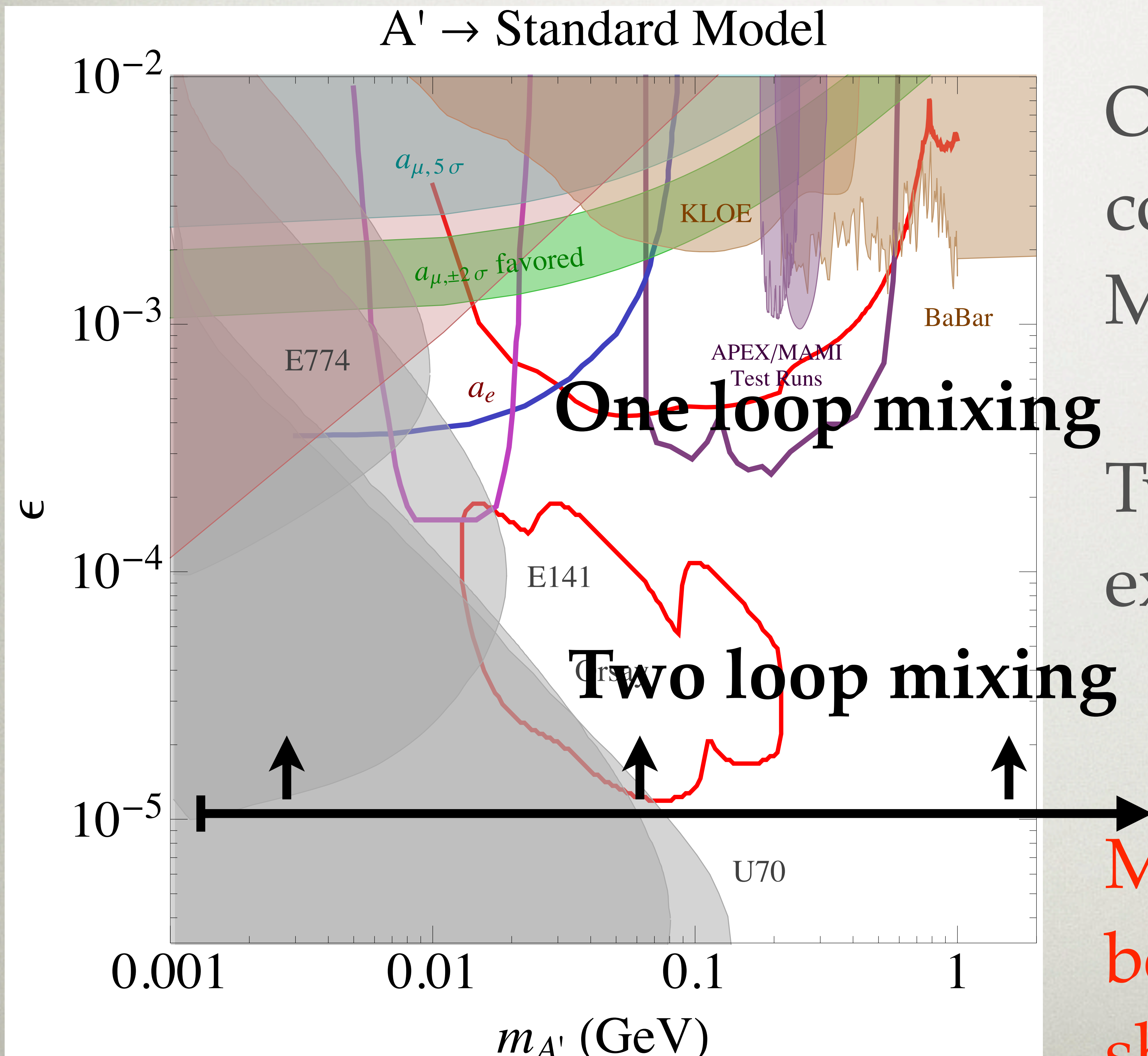
a motivated target of opportunity

“Top Down”-Motivated Region

(A′ Electron/Muon Decays)



Projections vs. "top-down"



One-loop region well covered below 500 MeV

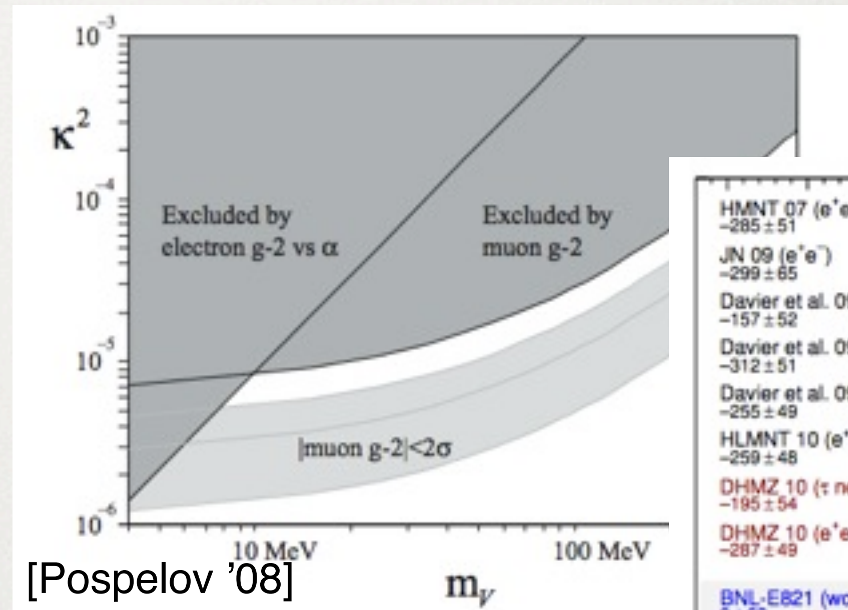
Two-loop region explored by HPS

Mass reach should be extended, and gap should be closed

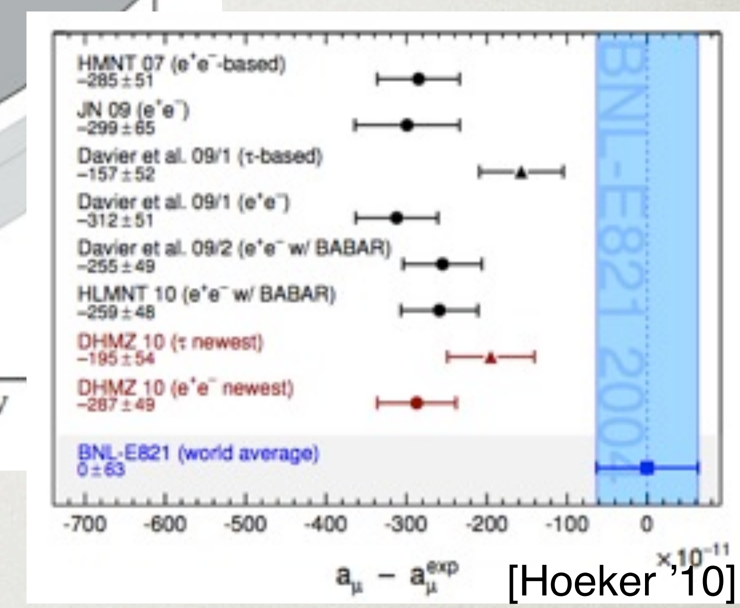
Target of Opportunity? Precision Anomalies

Muon g-2

$U(1)_D$ coupling modifies $(g\text{-}2)_\mu$, with correct sign. $\varepsilon \sim 1\text{-}3\ 10^{-3}$ can explain discrepancy with Standard Model



[Pospelov '08]

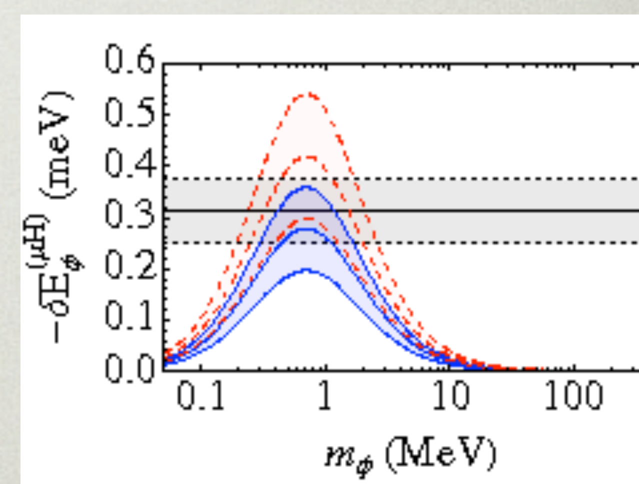


[Hoeker '10]

Muonic hydrogen

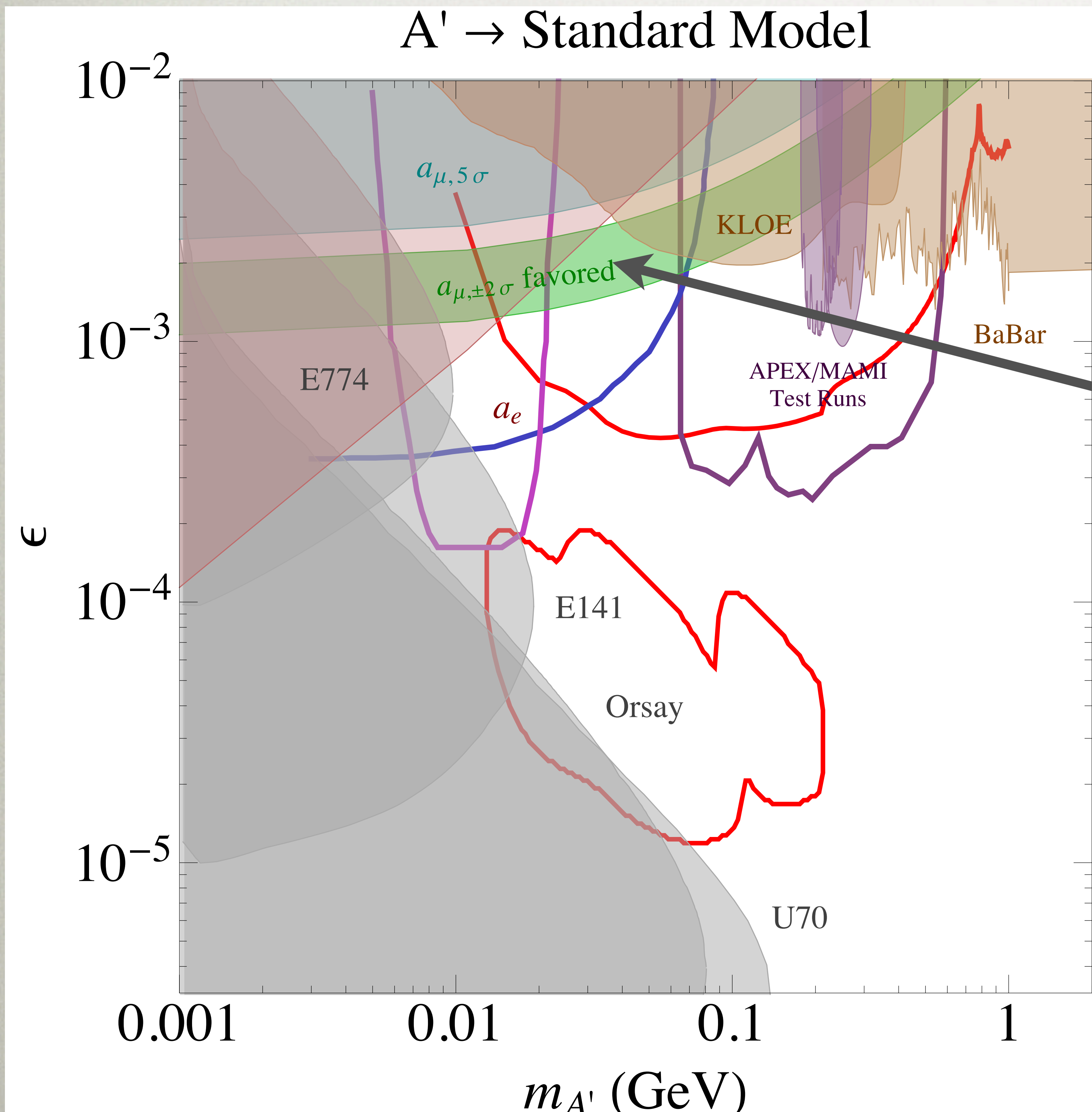
MeV-scale force carriers can explain the discrepancy between (μ^-,p) Lamb shift [Pohl et al. 2010] and other measurements of proton charge radius.

Requires couplings *beyond* kinetic mixing (lepton flavor-violating component)



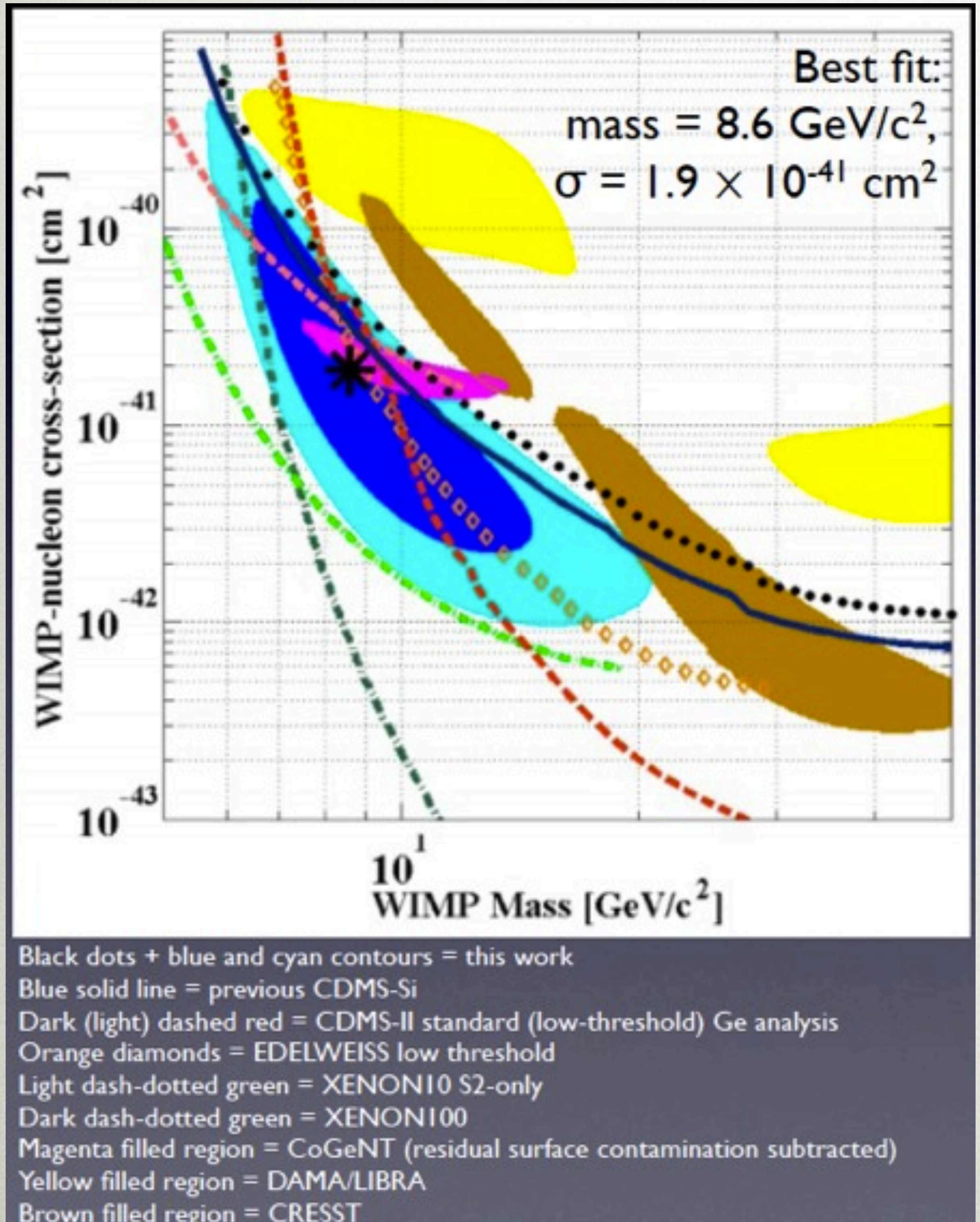
[Tucker-Smith & Yavin, 1011.4922]

Projections vs. Muon G-2



g-2 region for visible A′ decays can be completely explored

Target of Opportunity? Direct-Detection Anomalies

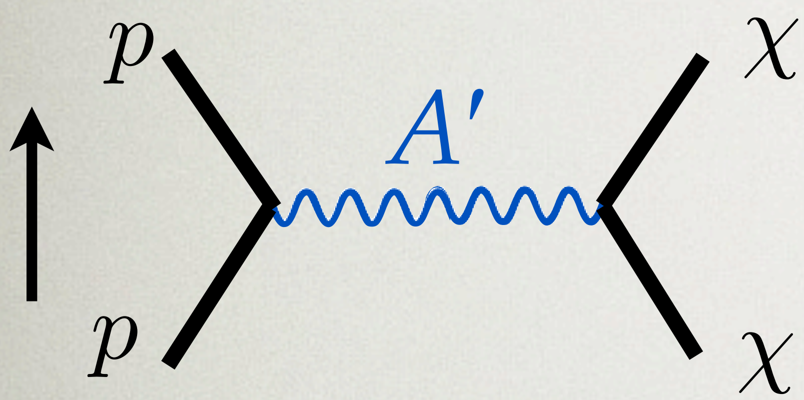


CDMS collaboration, 1304.4279

Several light dark matter direct detection hints

Dark matter interacting via dark photons is a viable explanation discussed at length in the literature

Target of Opportunity?
Direct-Detection Anomalies



$$\sigma_{p\chi} \approx 16\pi \frac{\alpha\alpha_D\epsilon^2 m_p^2 m_\chi^2}{m_{A'}^4 (m_\chi + m_p)^2}$$

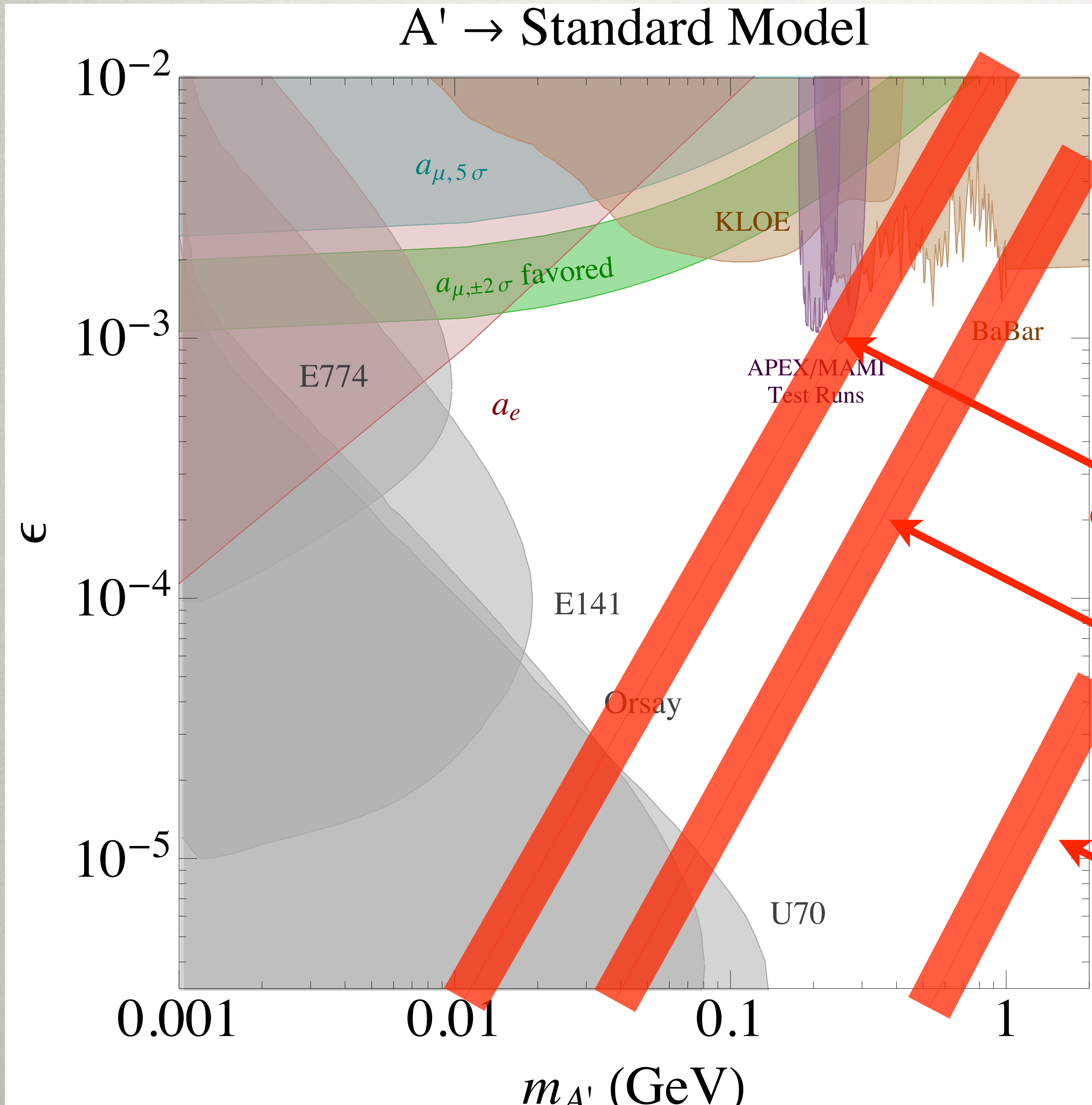
$$\approx 1.2 \times 10^{-40} cm^2 \left(\frac{\alpha_D \epsilon^2}{10^{-12}}\right)\left(\frac{GeV}{m_{A'}}\right)^4$$

Direct detection equally sensitive to *any* DM component

So best fit is given by: $\left(\frac{\alpha_D \epsilon^2}{10^{-12}}\right)\left(\frac{GeV}{m_{A'}}\right)^4 \sim \frac{\Omega_{DM}}{\Omega_\chi}$

(ratio of densities)

Target of Opportunity? Direct-Detection Anomalies



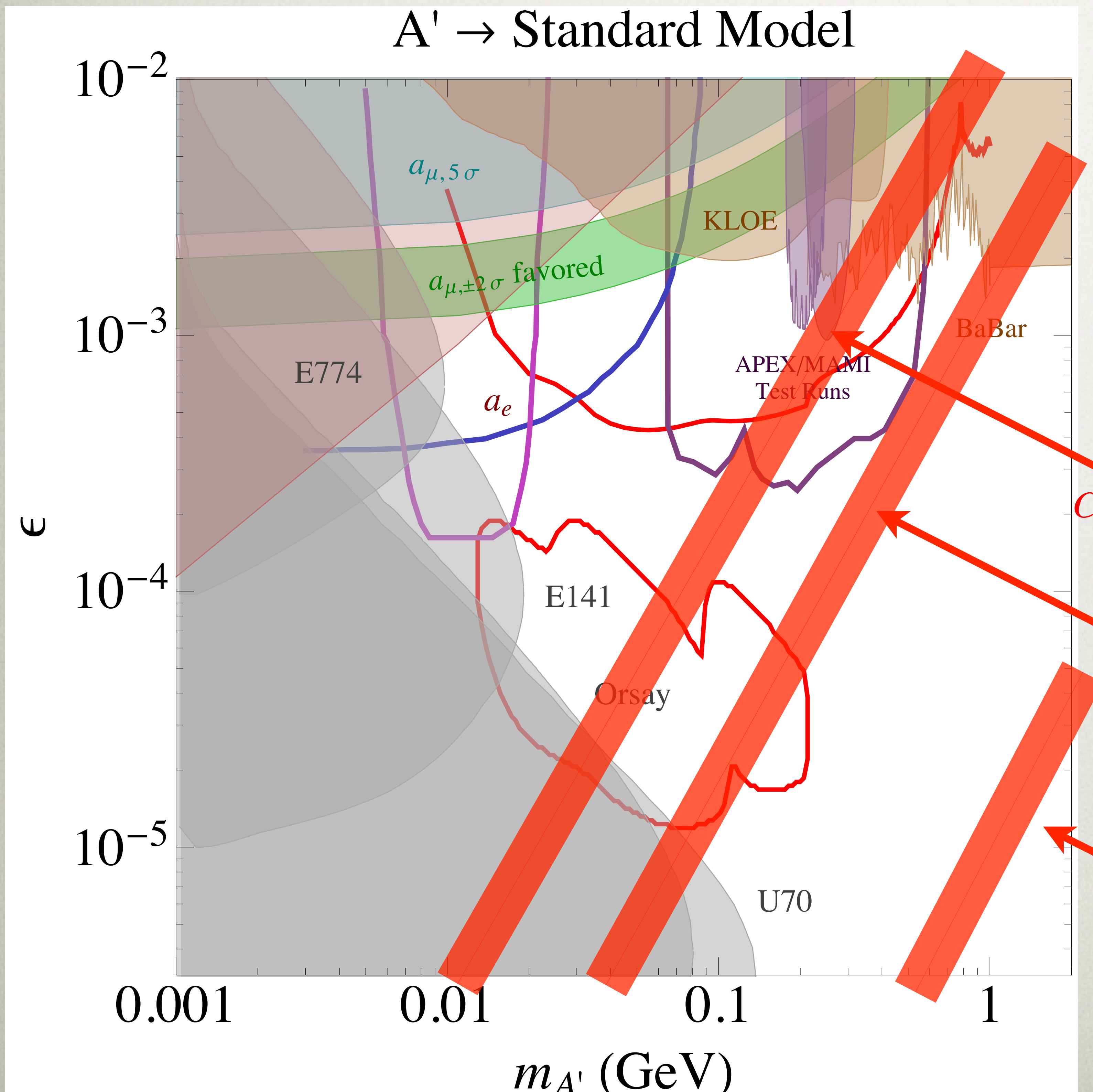
Region of interest depends on α_D and "DM" partial fraction Ω_χ/Ω_{DM}

$\alpha_D = 10^{-2}\alpha \quad \Omega_\chi/\Omega_{DM} = 10^{-4}$

$\alpha_D = \alpha \quad \Omega_\chi/\Omega_{DM} = 10^{-4}$

$\alpha_D = \alpha \quad \Omega_\chi/\Omega_{DM} = 1$

Projections vs. Direct-Detection



Will start to cover large direct-detection region, but will need to do better

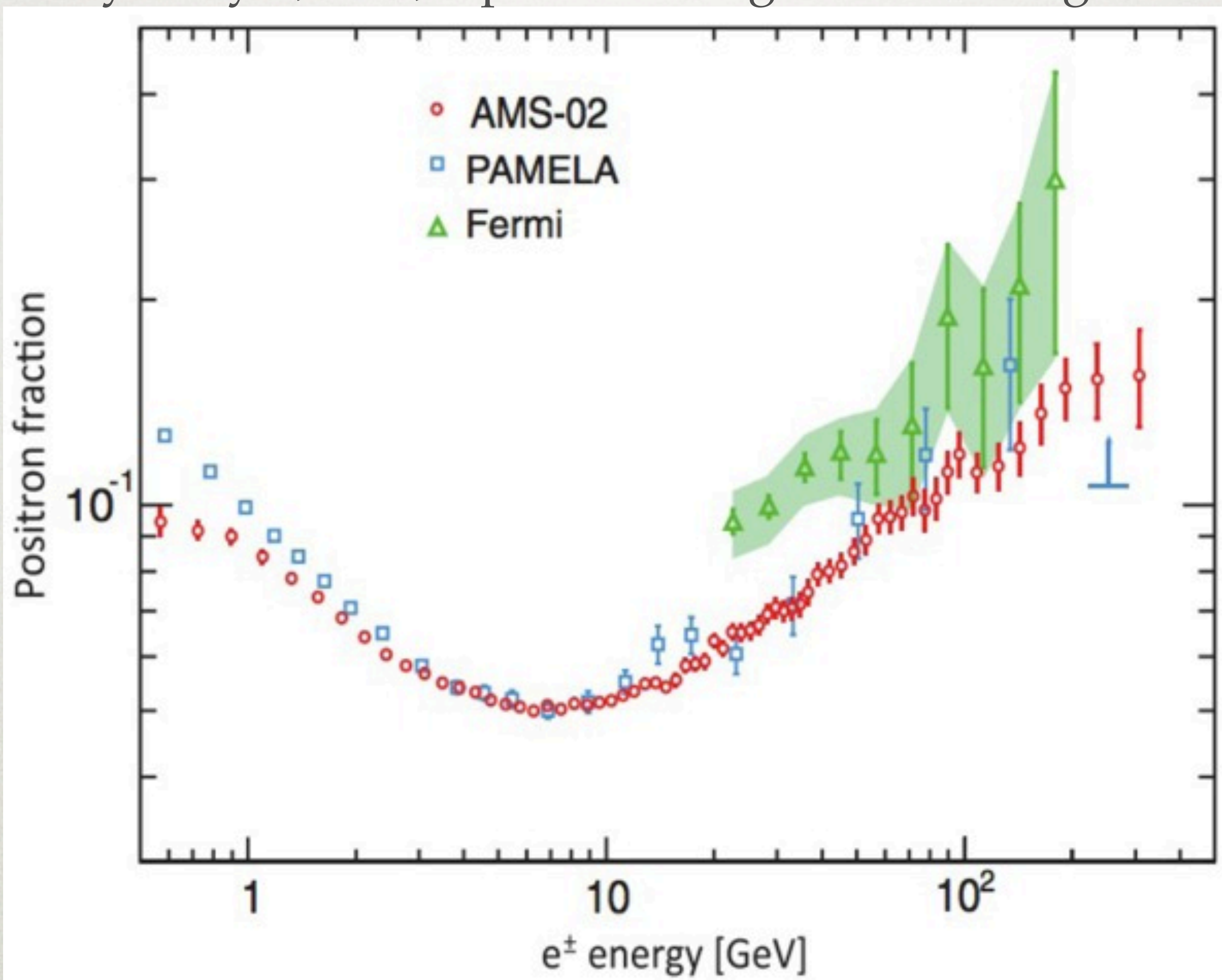
$\alpha_D = 10^{-2}\alpha \quad \Omega_\chi/\Omega_{DM} = 10^{-4}$

$\alpha_D = \alpha \quad \Omega_\chi/\Omega_{DM} = 10^{-4}$

$\alpha_D = \alpha \quad \Omega_\chi/\Omega_{DM} = 1$

Target of Opportunity? Cosmic Ray Anomalies

Tracy Slatyer, IFW, April 2013 Argonne Meeting



Increasing positron fraction may be due to DM annihilation/decay to A's

Target of Opportunity? Cosmic Ray Anomalies

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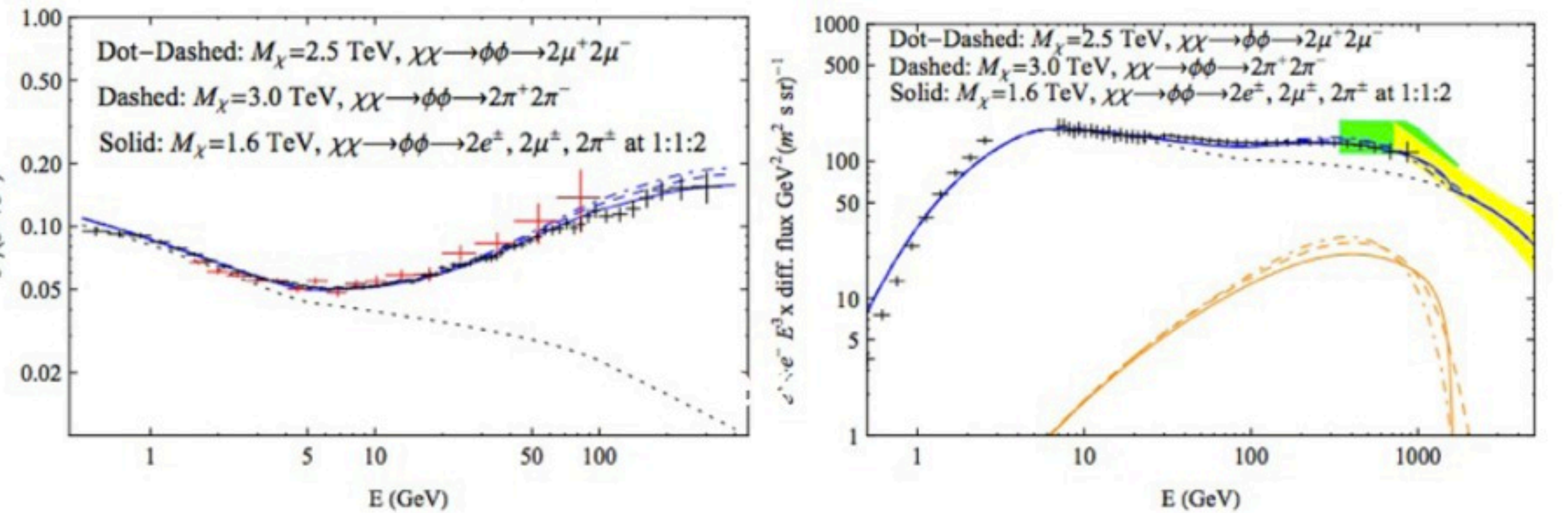
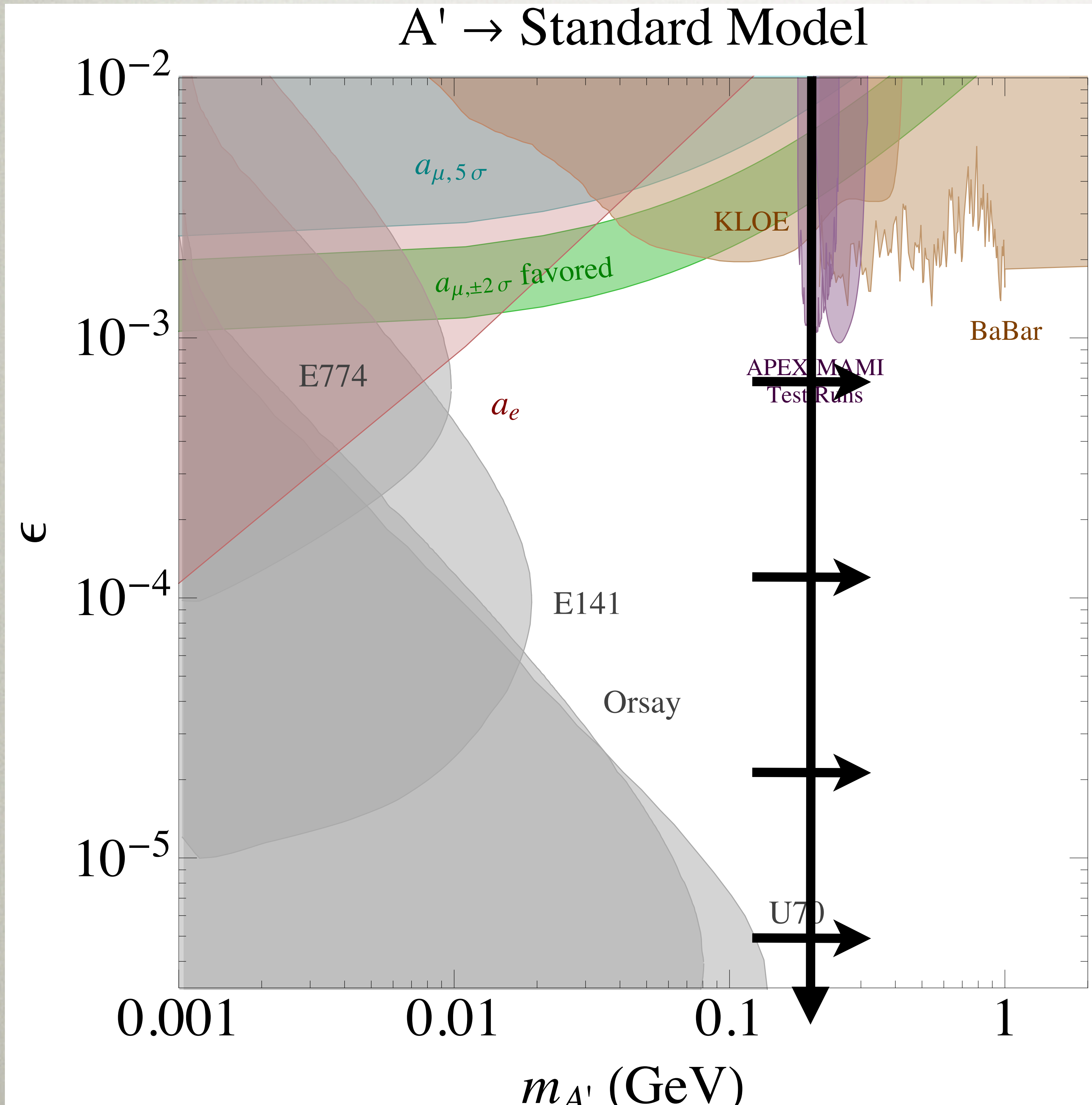


FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of $L = 8$ kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ($dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 100 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 100 GeV). The cross sections are the same as given in the caption of Fig. 5. With this cosmic ray background, the dark matter models shown can simultaneously accommodate the measurements of the cosmic ray positron fraction and the overall leptonic spectrum.

Cholis & Hooper 1304.1840

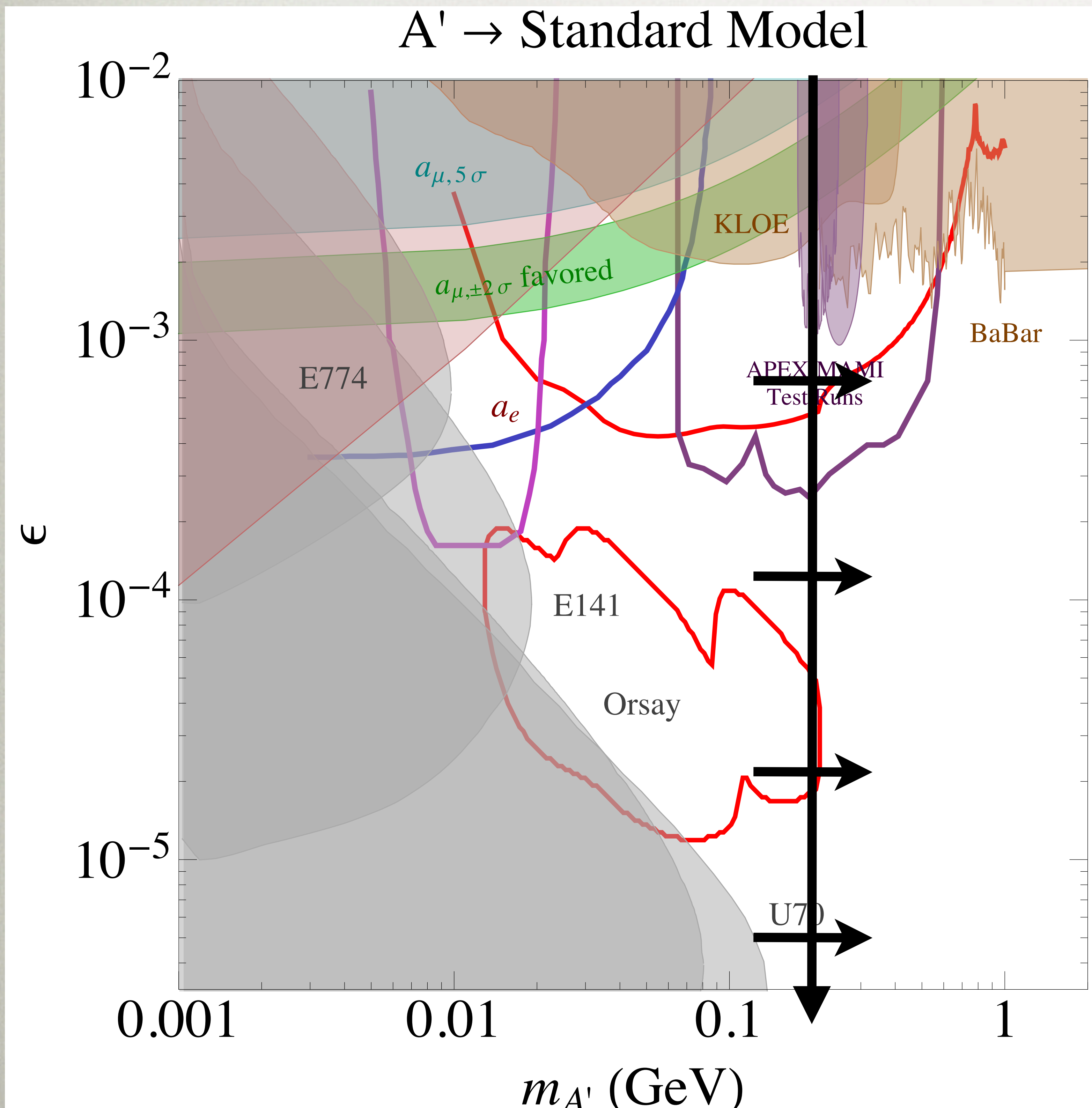
Fits to cosmic ray spectra prefer A' masses above the muon decay threshold (>210 MeV)

Target of Opportunity? Cosmic Ray Anomalies



Preferred by fits of cosmic ray data to ~few TeV DM annihilating to A's

Projections vs. DM Cosmic Ray



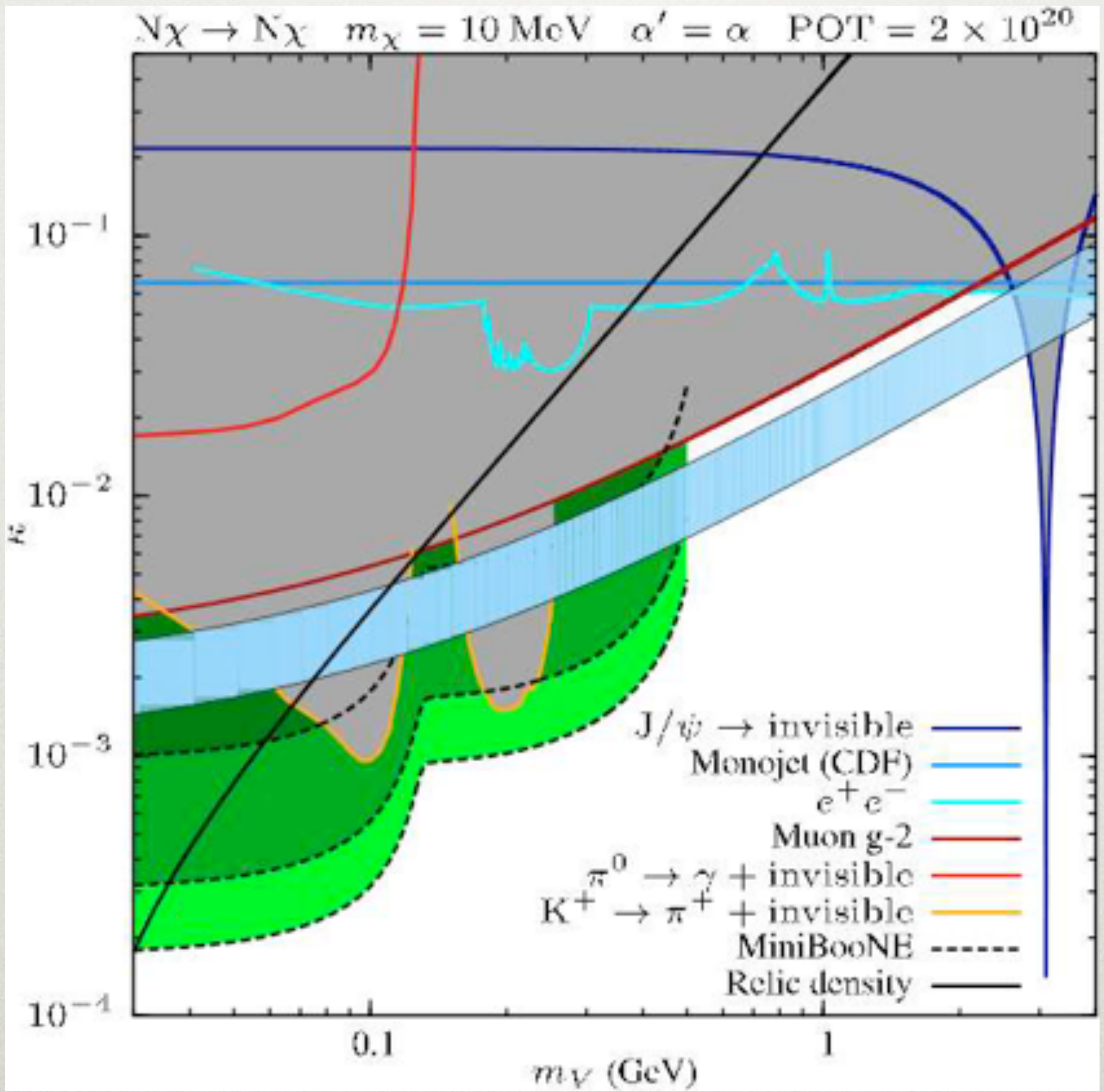
HPS and APEX will make progress, but will need to do better

Non-minimal dark sector or modified propagation consistent with lighter A'

Projections

(A′ invisible "dark matter" Decays)

sub- 500 MeV WIMP search using MiniBooNE

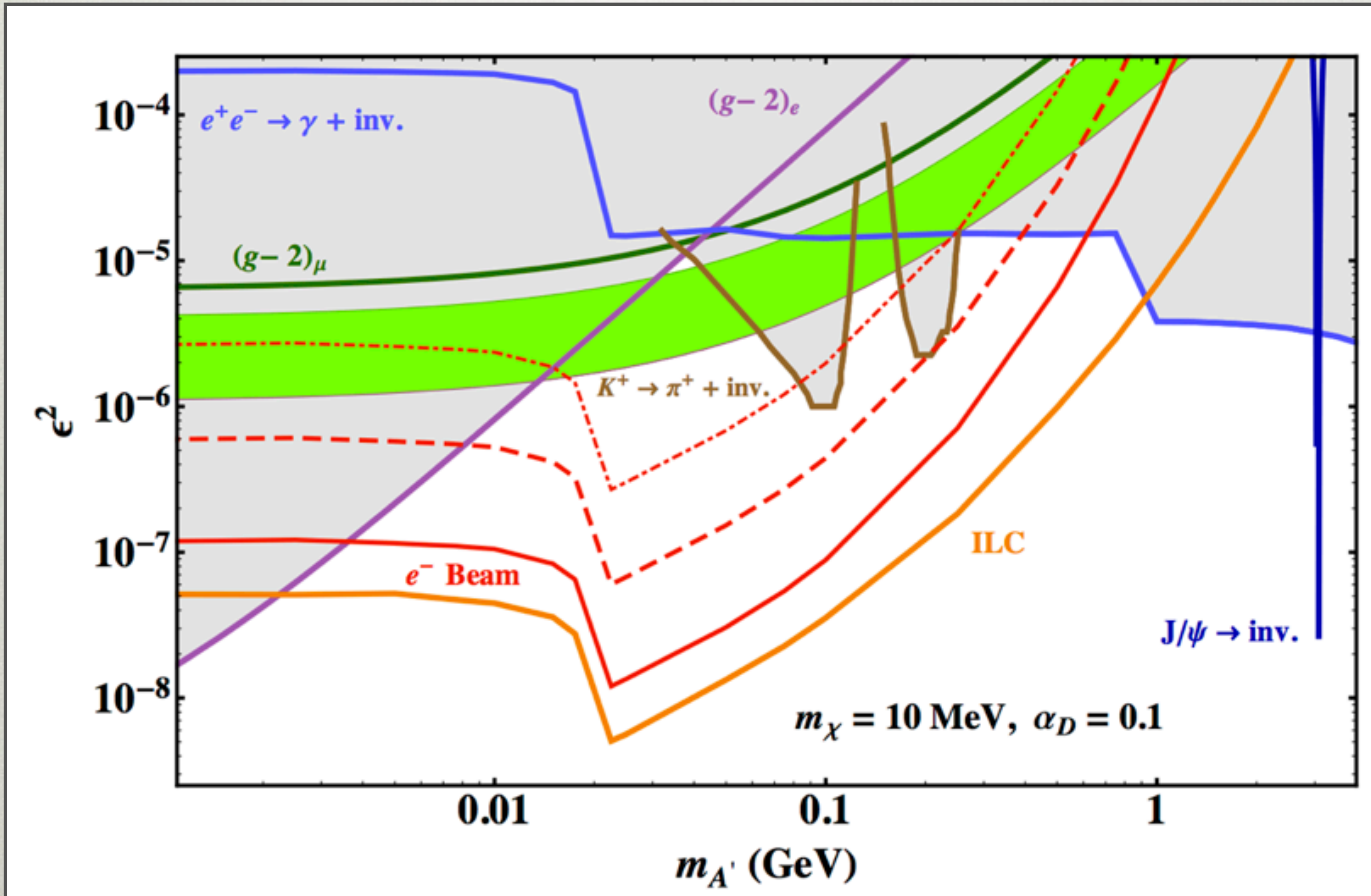


(see: arXiv:1211.2258 for proposal)

Projections

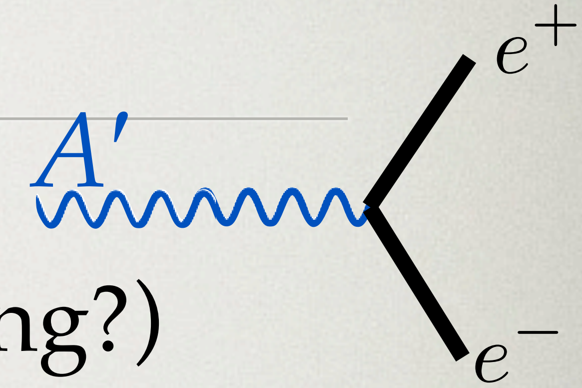
(A′ invisible "dark matter" Decays)

Potential searches using electron fixed-target

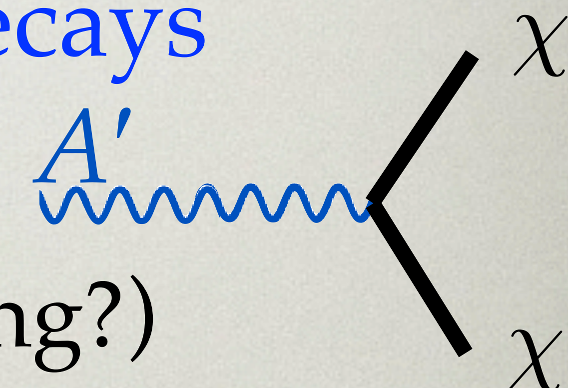


(Izaguirre, Krnjaic, PS, Toro)

10-Year Goals for "Heavy-Photon" Physics



- "Visible" Decays
  - (g_μ-2)–motivated region (<100% branching?)
  - Full perturbative coupling range ($\varepsilon \gtrsim 10^{-5}$) over widest mass range possible
  - Sensitivity to muons and pions to extend mass reach
  - Sensitivity to multi-stage dark sector decays



- "Invisible" decays
  - (g_μ-2)–motivated region (<100% branching?)
  - Full perturbative coupling range ($\varepsilon \gtrsim 10^{-5}$) over widest mass range possible
  - Probe dark matter masses from MeV to GeV range

10-Year Goals for "Heavy-Photon" Physics

Probe anomaly driven scenarios from precision, DM direct detection, and cosmic ray hints

In the process, discover and study True Muonium, try to carry out precision muon studies (parity violation?), probe extended Higgs sectors...etc.

We either discover new forces (or DM), or we close up a big window into dark sector physics at sub-GeV scales

Conclusions

- Dark Forces are an exciting window into physics **far beyond** the Standard Model
  - Possible connections to dark matter, muon g-2, and physics at very high energies
- Small-scale & novel experiments are pioneering the exploration of this physics
  - Will explore large new physics territory for direct A′ production and decay and discover rare SM physics
- Potential opportunities at many labs to directly produce dark matter and search for invisible A′ decays with unique sensitivity
- 10-year physics program continuing to leverage existing facilities has exciting discovery prospects

Thanks!